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PERFORMANCE AND EVALUATION OF A LIQUID-METAL PUMP FOR MERCURY SERVICE

by Sol H. Gorland, Roy A. Lottig, and Thomas P. Hecker

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ABSTRACT

An induction-motor-powered centrifugal pump operated successfully for 1455 hr at a mercury loop at 350° to 400° F (450 to 480 K) without maintenance. Approximately 1325 hr were at the steady-state condition of 11 570 lb/hr (5250 kg/hr) flow with a head of 83.2 ft (249 J/kg). Polyphenyl-ether-lubricated ball bearings were used in the pump.

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SUMMARY

An induction-motor-powered centrifugal pump operated successfully for 1455 hours in a mercury loop at 350° to 400° F (450 to 480 K) without maintenance. Approximately 1325 hours were at the steady-state condition of 11 570 pounds per hour (5250 kg/hr) flow with a head of 83.2 feet (249 J/kg). Polyphenyl-ether-lubricated ball bearings were used in the pump. To prevent intermixing of the mercury with the lubricant, a combination of static and dynamic seals was incorporated. There were no parametric excursions outside the envelope considered safe for 10 000 or more hours of operation.

INTRODUCTION

Centrifugal pumps for liquid-metals are required by Rankine-cycle space power systems in which zero external leakage, reliability, and component endurance are of primary interest. Other important design requirements are minimum size and weight, as well as high efficiency. In the development stage of a complex system, such as the SNAP-8 power conversion system, several copies of a given component are evaluated in order to ensure reproducibility of performance and to aid in the analysis of the results. The subject of this report is a motor-driven centrifugal pump operated for 1455 hours in a mercury loop at 350° to 400° F (450 to 480 K). Evaluation of some of the other mercury pumps are reported in references 1 and 2.

The mercury pump used ball bearings lubricated by polyphenyl ether. To prevent intermixing of the mercury with the lubricant, a visco pump and molecular pump were combined to separate and seal the two fluids during operation. At static and low speed operation, liftoff face seals were used. References 3 and 4 are comprehensive descriptions of the visco pump and molecular pump. An induction motor eliminated the need for brushes.

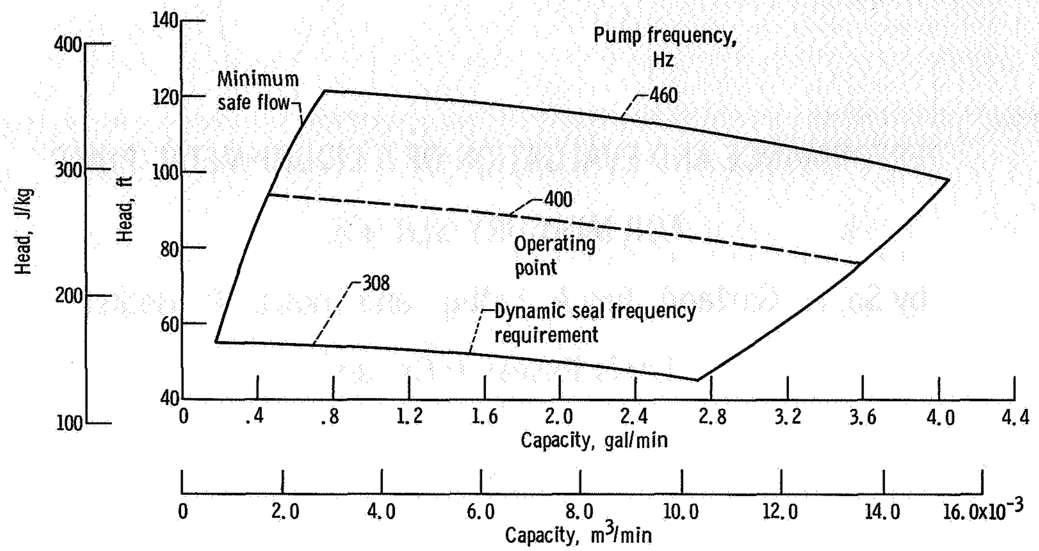


Figure 1. - Operational envelope. Head versus capacity.

The purpose of this investigation was to determine experimentally if the pump would perform satisfactorily in a SNAP-8 system without maintenance. Consequently, a mercury pump was tested at the Lewis Research Center from September through November 1967. The operating envelope for minimum requirements is shown in figure 1.

TEST FACILITY

The test facility in which the pump was operated was designed for performance testing of a simulated SNAP-8 system. SNAP-8 is a 35 kW nuclear-electric space power system operating on the Rankine cycle. As shown by figure 2 a four-loop system was used in the test, two NaK loops, one mercury loop, and an oil lubricant-coolant loop. The four-loop simulated SNAP-8 system is described in reference 5.

The mercury pump was powered by two different sources, namely, facility power and turbine-alternator power. A facility 200 to 2000 hertz variable-frequency motor-generator set, previously set for approximately 400 hertz ±5 percent was used to start the pump. When the system reached steady state at the design operating condition, the pump was switched to the SNAP-8 turboalternator. The turboalternator speed was controlled and output frequency maintained at 400 hertz ±1 percent.

In the test facility, the pump was run with strainer screens in the inlet line and a filter in the outlet line. An important pump consideration for mercury systems is that a high degree of cleanliness is required in order to prevent corrosion and to attain high heat-transfer effectiveness (refs. 6 and 7).

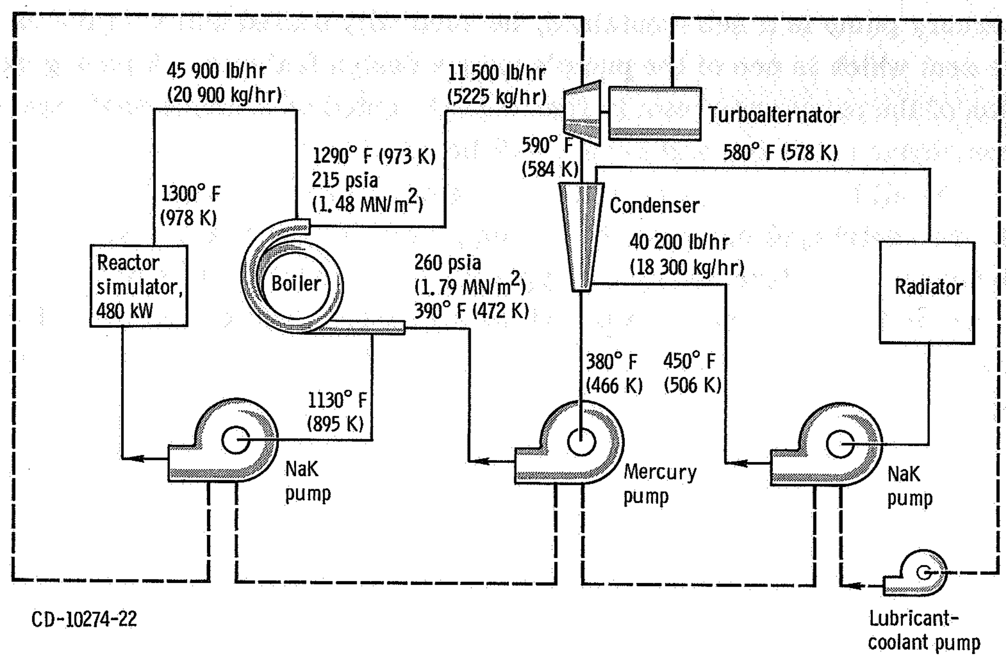


Figure 2. - Simulated SNAP-8 system.

The mercury pump can be run without mercury for several hours to perform a checkout of the electrical system. However, the static seals require attention during startup and shutdown in order to prevent excessive wearing which would lead to intermixing of the fluids during succeeding starts and shutdowns. As a safety precaution during shutdown, the coolant fluid inlet valve must be closed before the outlet valve so that the pump can scavenge the coolant fluid. This prevents oil from remaining in the cavity and having to rely on the static seals to prevent intermixing with the mercury. Synchronization of these valves was then incorporated.

INSTRUMENTATION

Instrumentation necessary to evaluate pump performance consisted of: flowmeters, pressure transducers; thermocouples; power, current, and voltage transducers; and electromagnetic speed pickups. Liquid-mercury flow was measured by a calibrated venturi downstream of the pump. Descriptions of the instrumentation, their ranges, accuracies, and methods of calibration are given in reference 8.

PUMP DESCRIPTION

The mercury pump is a self-contained, hermetically sealed unit with the exception of the space seal which is one of the pump's unique design features. A photograph and cross section of the pump are shown in figure 3. Mounted on a single shaft are a centrifugal pump, dynamic seals, a 208-volt, 400-hertz, 3-phase induction motor, and angular-contact ball bearings. A jet pump upstream of the centrifugal pump suppresses cavitation in the centrifugal pump during startup, when the net positive suction head is low. The bearings are lubricated by a polyphenyl-ether fluid which is also circulated through the motor-housing coolant coils and the space-seal heat exchanger. The pump with its motor weighs approximately 150 pounds (68 kg) and is designed to operate at 500° F (530 K).

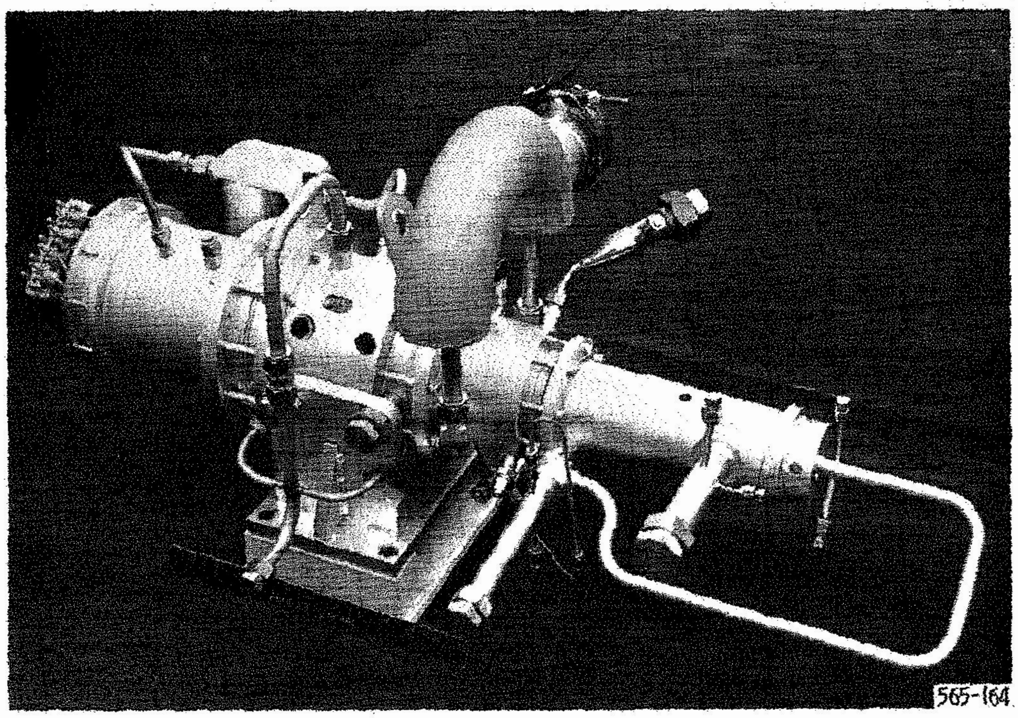
Seals

The space seal, described in references 3 and 4, minimizes fluid losses to space and prevents intermixing of the working fluid (mercury) and the lubricant. Static seals prevent intermixing when the pump is idle.

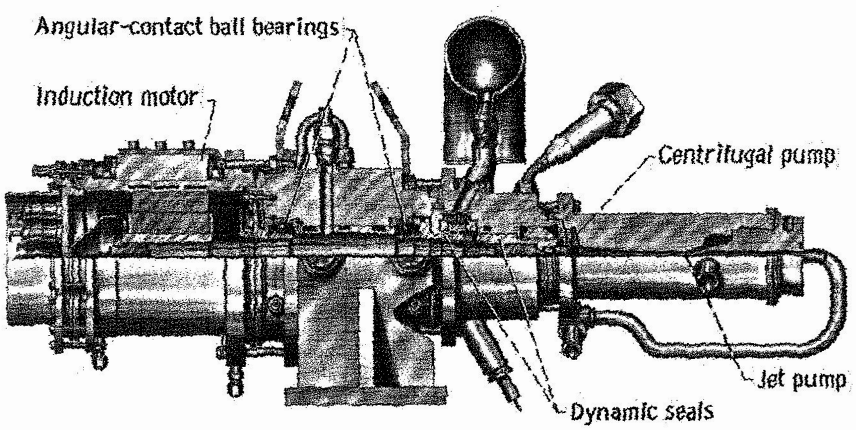
The static seal, necessary for startup and shutdown, consists of two bellow-type carbon face seals which seal against opposite surfaces of a rotating ring, one seal on the mercury side and the other on the lubricating fluid side. To prevent seal wear during long-term operation and to reduce power losses, the static seals are lifted off the rotating ring by pressurizing the bellows. The static liftoff seals were lifted by pressurizing with argon to 200 to 225 psia (1.38 to 1.55 MN/m^2). The dynamic seals then take over the sealing function.

The dynamic sealing is accomplished by a combination of a visco pump/molecular pump on the mercury side and a slinger/molecular pump on the oil side. In between these two systems is a vent to space or a vacuum as used in the test facility. The visco pump is of a helical screw design. It pumps mercury back into the centrifugal pump and maintains a liquid-vapor interface between the visco pump and the molecular pump. The liquid-vapor interface is maintained at approximately 300° F (425 K) by the space seal coolant to minimize boiloff. The molecular pump's function on the mercury side is to pump escaping mercury molecules back to the liquid-vapor interface in the visco pump.

The dynamic seal on the lubricant side is maintained by a slinger and molecular pump. The slinger developes a stable liquid-vapor interface, while the molecular pump returns lubricant molecules to the interface.



(a) Photograph.



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(b) Cross section.

Figure 3. - SNAP-8 mercury pump.

Motor

The 3-phase, 208-volt, 400-hertz induction motor is fitted with hermetically sealed, ceramic-electrical and thermocouple terminals for internal instrumentation. A slinger prevents excessive lubricating fluid from entering the stator cavity. Excessive lubricating fluid entering this cavity would increase both power consumption and winding temperatures.

RESULTS AND DISCUSSION

The mercury pump was run for 1455 hours with all but approximately 20 hours at system operating temperatures of 350° to 400° F (450 to 480 K). Eighteen startups were made. As shown in table I most of these were short-duration tests on the pump or to check the pump coolant system.

TABLE I. - MERCURY PUMP

OPERATION

Start	Run duration, hr	Remarks
1	0.9	System checkout
2	.2	System checkout
3	1.2	Dry run (no Hg)
4	.05	System checkout
5	.05	System checkout
6	.8	System checkout
7	.02	System checkout
8	.01	System checkout
9	.04	System checkout
10	1.6	System checkout
11	.2	Dry run (no Hg)
12	1.6	System checkout
13	2.2	System checkout
14	.01	System checkout
15	.01	System checkout
16	.01	System checkout
17	354.7	System test
18	1091.8	System test
Total	1455.5	

Operation of the space seal proved satisfactory in minimizing leakage. Some leakage was found to have occurred across the static seals after shutdown; however, quantitative measurements could not be made.

Data were taken over the entire 1455 hours of pump operation during steady-state conditions, startups, early system testing, and the final shutdown. For comparison, all data presented in the performance curves have been corrected to the speed reported in reference 2, that is, 7850 rpm. The corrections were made using the usual similarity relations (e.g., in ref. 9) for flow, head, and power.

The mercury pump was operated at speeds varying from 7870 to 8150 rpm with the steady-state endurance speed maintained between 7870 and 7900 rpm. The head-flow curve produced (fig. 4) was lower than for the pump of reference 2, with variations of approximately $1\frac{1}{2}$ feet (4.5 J/kg) at 0.7 gallon per minute (2.6×10^{-3} m^3/min) and 5 feet (15 J/kg) at the endurance condition of 1.775 gallons per minute (6.7×10^{-3} m^3/min). There appears to be no significant change in pump performance with time. Early data were taken during the first 20 hours of operation while the late data were taken during the last 30 hours of operation.

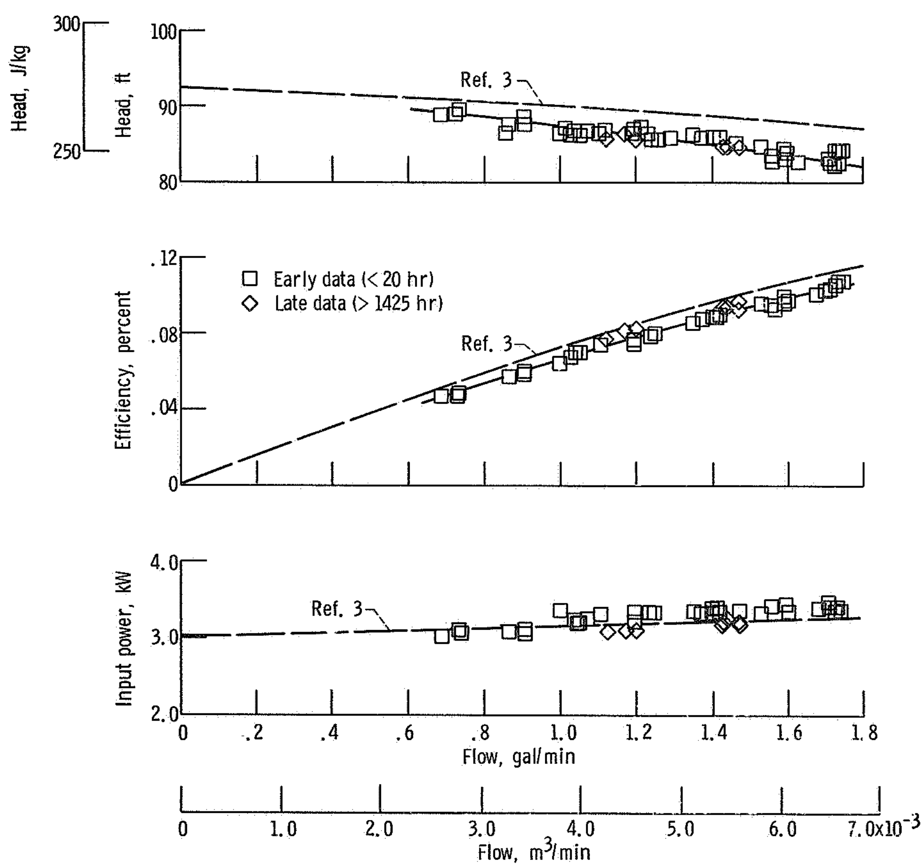

Figure 4. - Performance curve for mercury pump corrected to 7850 rpm.

Input power was approximately the same as for the pump tested in reference 2. The power was approximately 120 watts higher in early testing and 50 to 70 watts lower at the end of the test run. This could possibly be due to drift in the instrumentation since the change is within the experimental uncertainties of 5 percent for the power measurements. Calibration after the test supports the later data.

Corresponding to the head-flow and power curves of figure 4, the pump efficiency was found to be 0.005 lower at 0.7 gallon per minute (2.6×10^{-3} m^3/min) than the pump tested in reference 2 and 0.01 lower at 1.775 gallons per minute (6.7×10^{-3} m^3/min). The experimental inaccuracy present in this curve for the efficiency is 0.01.

In the mercury pump, waste energy is removed by the coolant fluid. The oil coolant loop is described in reference 10. There are three areas in the pump where heat is removed; the bearing cavity, the motor heat exchanger, and the space-seal heat exchanger. As seen in figure 5 the bearing heat loss is not affected by flow if the speed is constant. This is expected in a pump with ball bearings. The heat removed is approximately 250 watts. The motor heat loss, however, will change with load. It varied from 200 watts at 0.7 gallon per minute (2.6×10^{-3} m^3/min) to 270 watts at 1.775 gallons per minute (6.7×10^{-3} m^3/min). The data scatter in both cases is small considering the 10° to 15° F (5 to 8 K) temperature differential. Thermocouple accuracy $\pm 2^\circ$ F (1 K) is a significant portion of the power which was calculated using a heat balance. The space-seal heat exchanger produced a 1° to 2° F (1/2 to 1 K) change in the oil temperature across it, which, although being less than the accuracy of the measuring instruments, produced approximately a 500-watt heat loss.

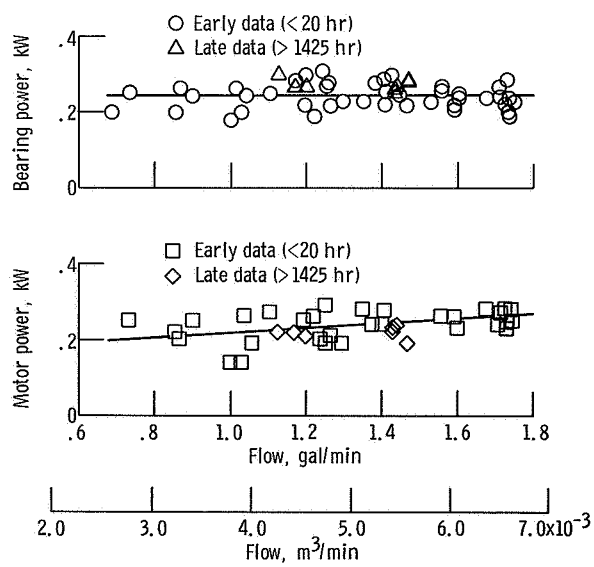

Figure 5. - Power transferred to lubricant-coolant fluid by mercury pump.

TABLE II. - MERCURY PUMP PERFORMANCE DATA

	Pump jet centrifugal flow		Inlet temperature		Speed, rpm	Inlet pressure		Outlet pressure		Head	
	lb/hr	kg/hr	^{o}F	K		psia	kN/m^2	psia	MN/m^2	ft	J/kg
Design	11 500	5225	505	534	7800	10.5	72.4	400.5	2.76	69.5	208
Test data (ref. 2)	11 500	5225	500	532	7850	10.5	72.4	498.5	3.44	87	260.5
Test data (this report)	11 570	5250	400	477	7900	18.8	130.0	490.6	3.38	83.2	249

	Hydraulic power, kW	Efficiency	Motor electrical efficiency	Motor overall efficiency	Input power, kW	Power factor	Overall efficiency
Design	0.30	0.220	0.902	0.483	2.84	0.68	0.1055
Test data (ref. 2)	.38	-----	-----	-----	3.30	.706	.1145
Test data (this report)	.36	-----	-----	-----	3.47	.776	.1045

Table II is a comparison of the pump performance with the design conditions and with reference 2. The data presented are not corrected for speed. Individual data on either the pump or motor could not be obtained in the test facility.

Figure 1 taken from reference 1 shows the operational envelope for the mercury pump. The actual operational point of the pump tested is marked. This pump is well within the envelope which is considered safe for the 10 000 hours of operation necessary for the SNAP-8 system. However, the long-term operating head was 5.0 feet (15 J/kg) less than the design head.

SUMMARY OF RESULTS

Analysis of the performance of a motor-driven centrifugal pump for mercury service operated in a simulated SNAP-8 system yielded the following results:

1. The pump operation successfully with no significant changes in pump performance for 1455 hours. No structural or material problems were encountered during the entire test.

2. Eighteen start-stop cycles were performed on the pump. The longest continuous run was 1092 hours.

3. Operation of the space seal proved satisfactory in minimizing leakage. Some leakage was found to have occurred across the static seals after shutdown; however, quantitative measurements could not be made.

4. The pump operated at 7900 rpm with a flow of 11 570 pounds per hour (5250 kg/hr) and produced a head of 83.2 feet (249 J/kg) at an overall efficiency of 0.105. The head is approximately 5.0 feet (15 J/kg) lower than previously tested pumps, causing the efficiency to be approximately 0.01 lower.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 10, 1968,
701-04-00-02-22.

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